

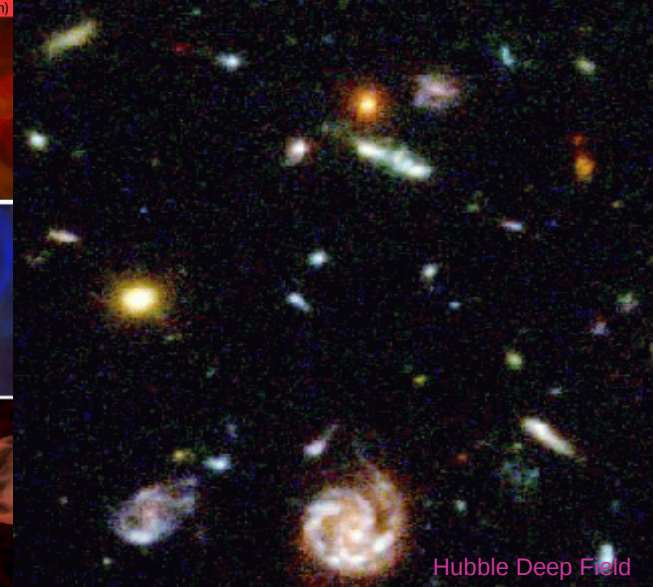
Evolution of Massive Stars and Nucleosynthesis

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Stan Woosley
Weiqun Zhang
Candace Joggerst
Ken Chen
Pamela Vo**

Overview

- **A Brief History of Time – Two Tales**
- **The Life of a Massive Star**
- **Nucleosynthesis in Massive Stars**
- **Pop III Stars**
- **Summary**

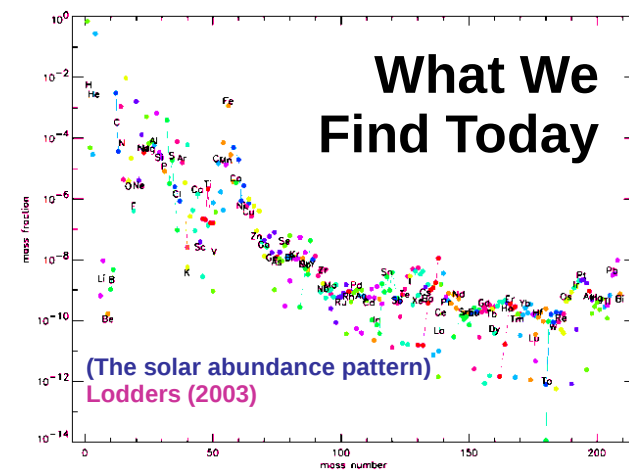
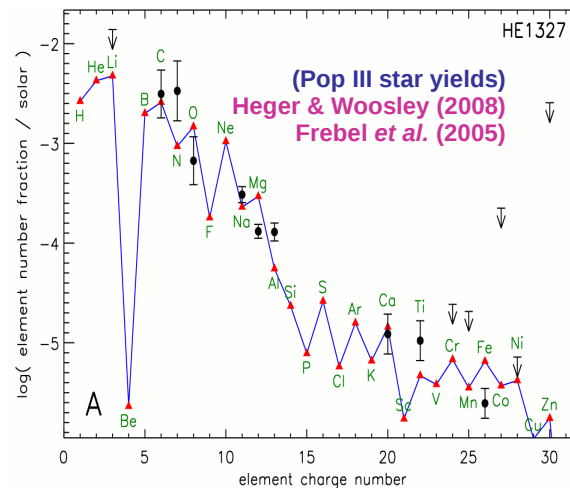
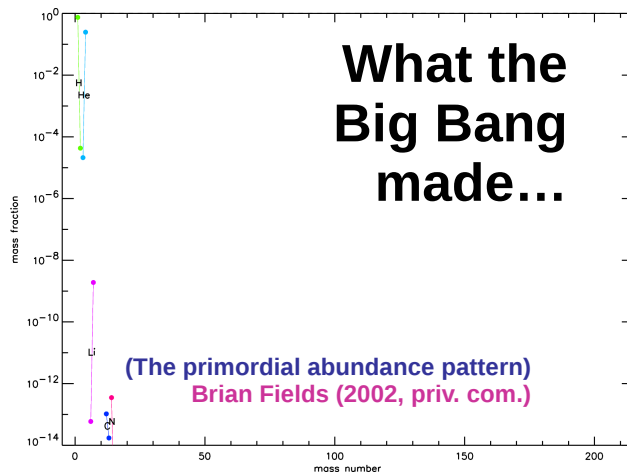
Cosmic Dark Age



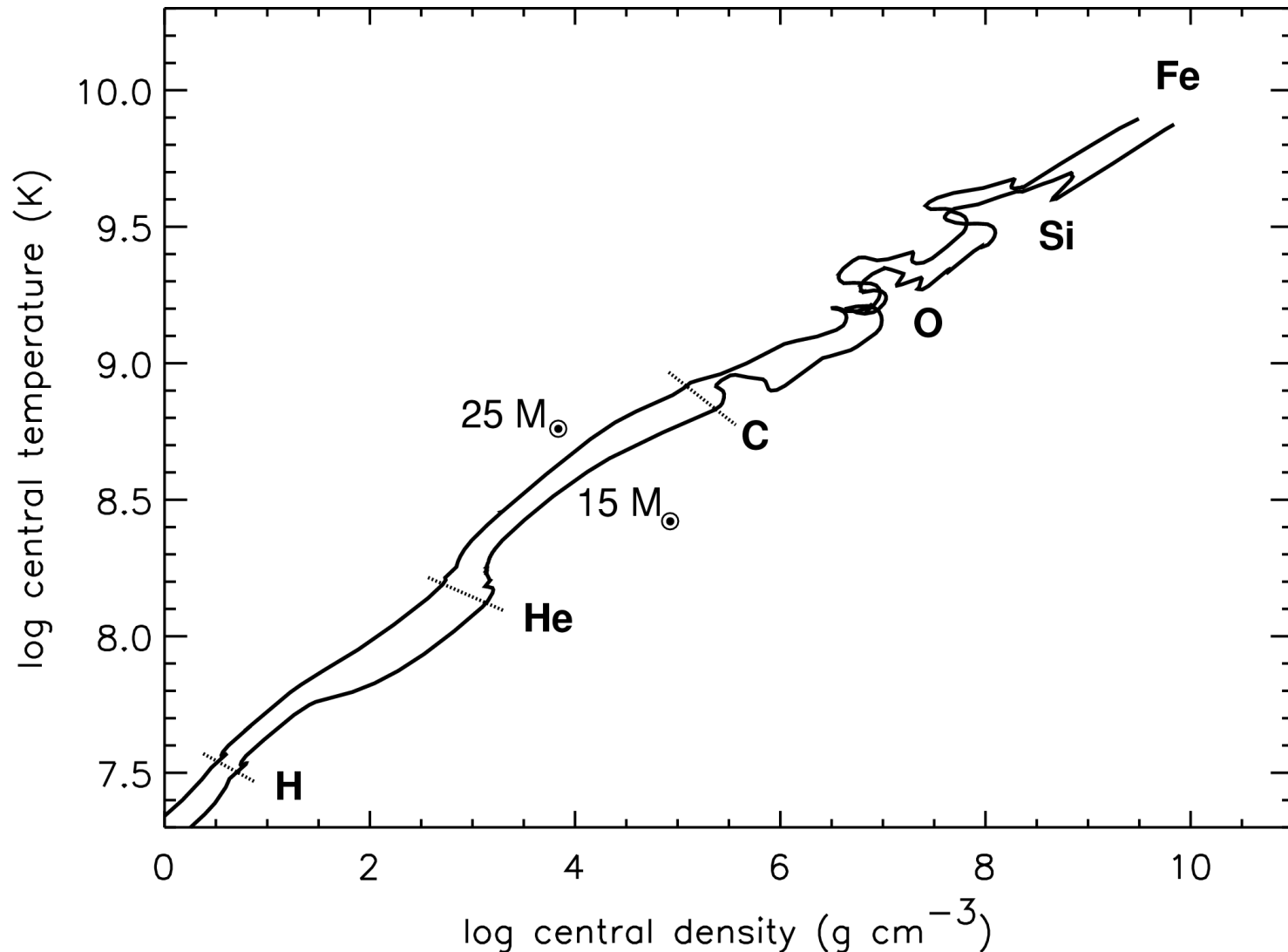
(after recombination)

© Alexander Heger

time



Once formed, the evolution of a star is governed by gravity:
continuing contraction
to higher central densities and temperatures



Evolution of
central
density and
temperature
of 15 M_{\odot}
and 25 M_{\odot}
stars

Nuclear burning stages

(20 M_☉ stars)

Fuel	Main Product	Secondary Product	T (10 ⁹ K)	Time (yr)	Main Reaction
H	He	¹⁴ N	0.02	10 ⁷	^{CNO} 4 H → ⁴ He
He	O, C	¹⁸ O, ²² Ne s-process	0.2	10 ⁶	3 He ⁴ → ¹² C ¹² C(α, γ) ¹⁶ O
C	Ne, Mg	Na	0.8	10 ³	¹² C + ¹² C
Ne	O, Mg	Al, P	1.5	3	²⁰ Ne(γ, α) ¹⁶ O ²⁰ Ne(α, γ) ²⁴ Mg
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	¹⁶ O + ¹⁶ O
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	²⁸ Si(γ, α)...

Neutrino losses from electron/positron pair annihilation

- Important for carbon burning and beyond
- For $T > 10^9$ K (about 100 keV), occasionally:

$$\gamma \rightarrow e^+ + e^-$$

and usually

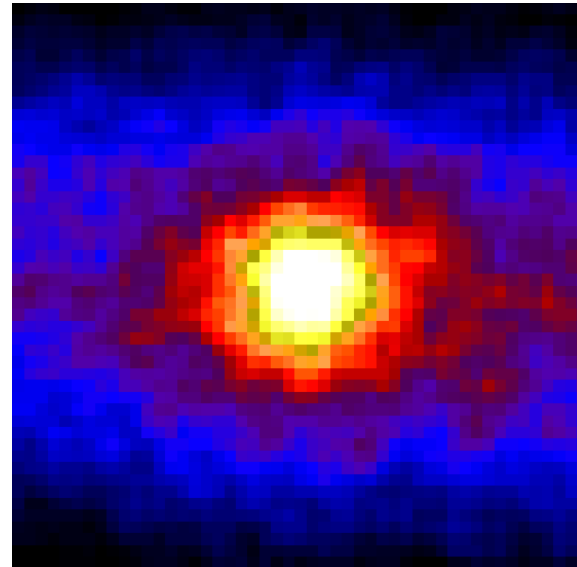
$$e^+ + e^- \rightarrow 2\gamma$$

but sometimes

$$e^+ + e^- \rightarrow \nu_{\bar{e}} + \nu_e$$

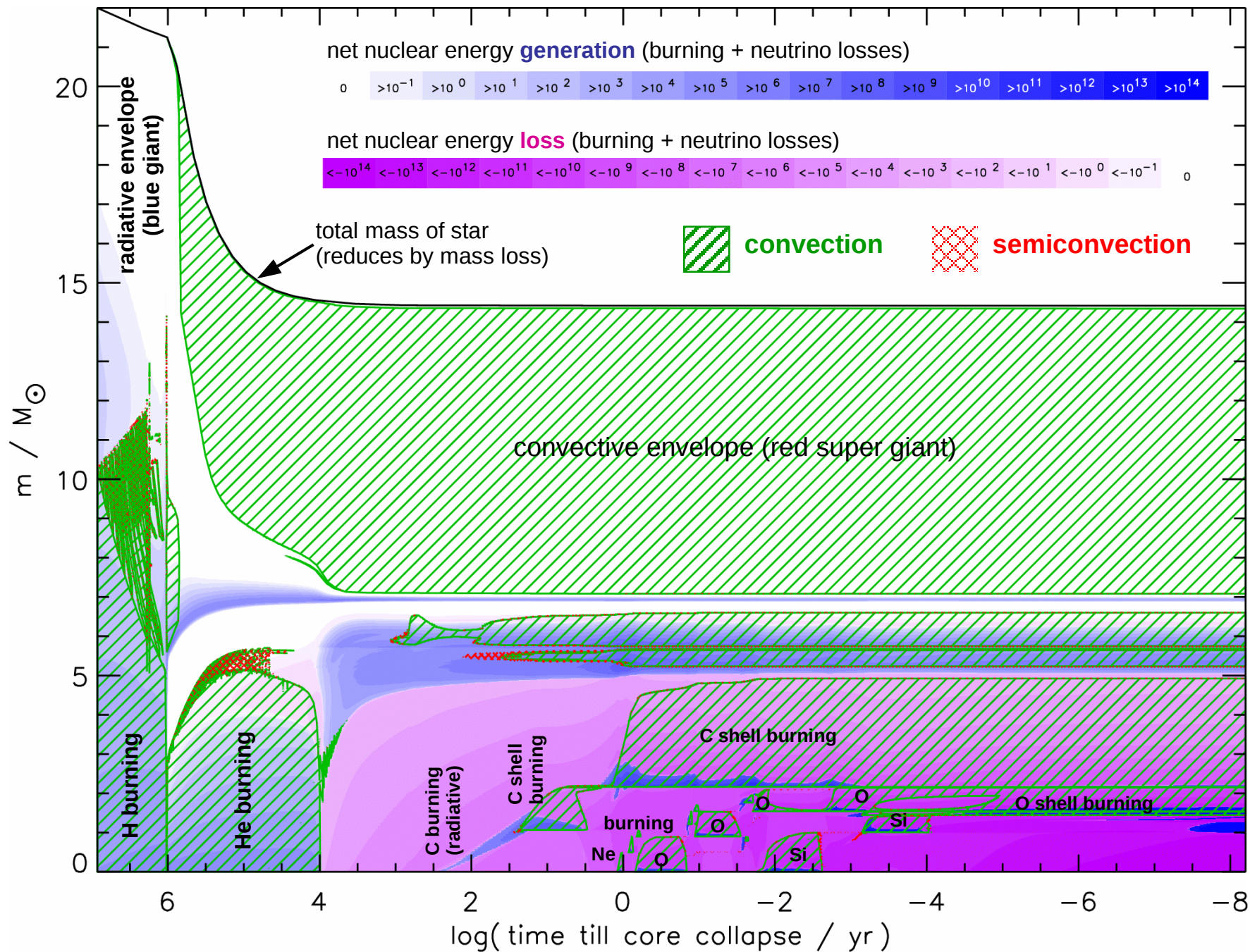
-
- The neutrinos exit the stars at the speed of light while the e^+ , e^- , and the γ 's all stay trapped.

- This is an important energy loss with $\epsilon_{\nu} \approx -10^{15} (T/10^9 \text{K})^9 \text{ erg g}^{-1} \text{ s}^{-1}$
- For carbon burning and beyond, each burning stage gives about the same energy per nucleon, thus the lifetime goes down as T^{-9}



The sun as seen by Kamiokande





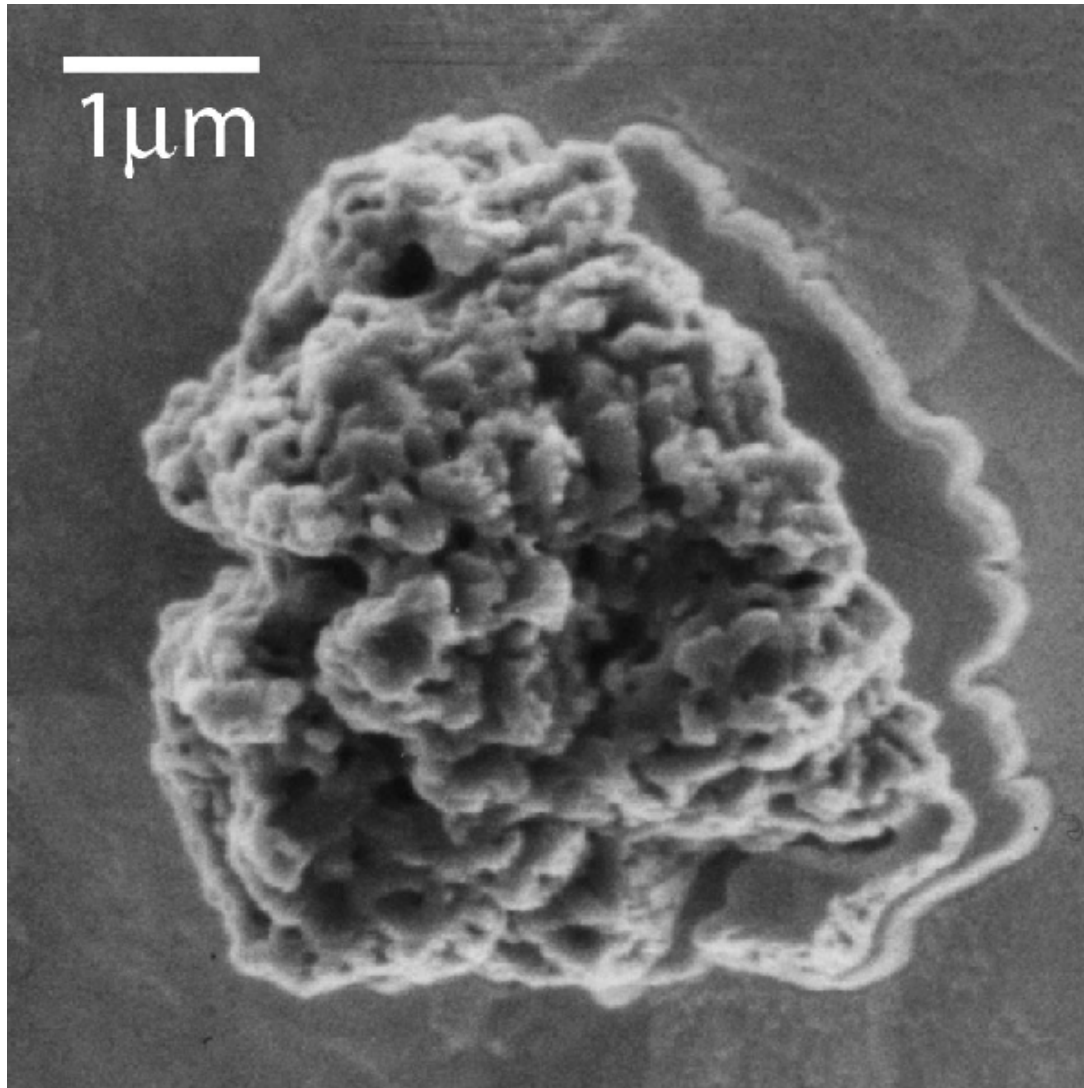
Explosive Nucleosynthesis

in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	<i>r</i> -process	-	>10 low Y_e	1	$(n,\gamma), \beta^-$
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}\text{O} + ^{16}\text{O}$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	$(\gamma,\alpha), (\alpha,\gamma)$
		p-process $^{11}\text{B}, ^{19}\text{F},$ $^{138}\text{La}, ^{180}\text{Ta}$	2 - 3	5	(γ,n)
		ν -process		5	$(\nu, \nu'), (\nu, e^-)$

Presolar grains

Direct access to pristine SN nucleosynthesis?



However:

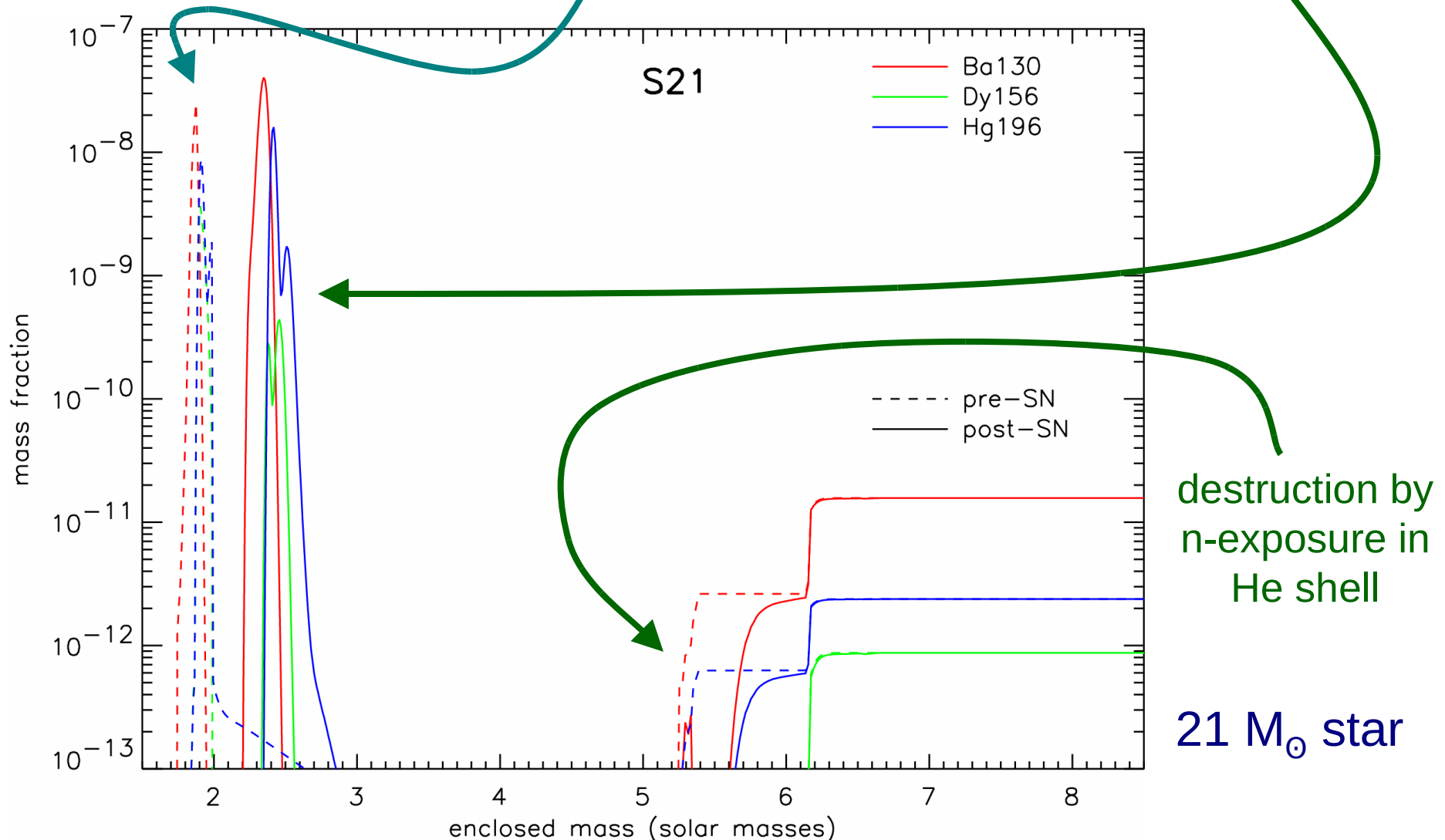
need to understand

- chemistry
- condensation
- SN mixing
- implantation

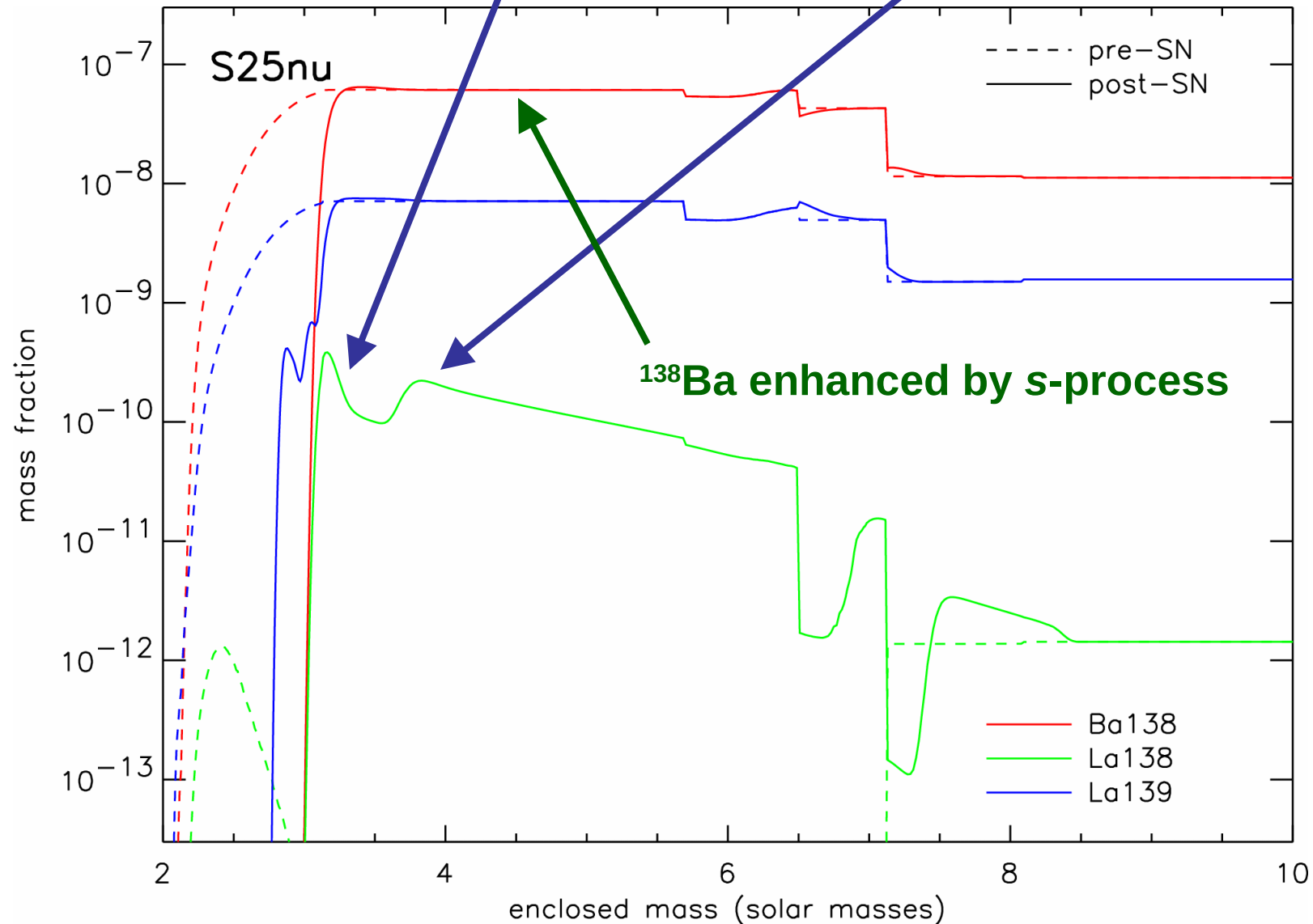
see Denault, Clayton & Heger (2003)

“Relocation” of the γ -process

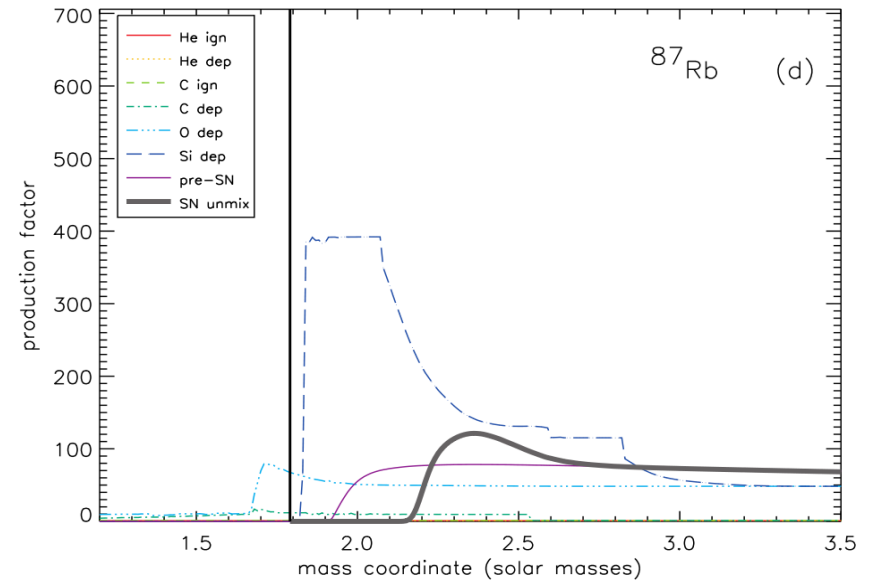
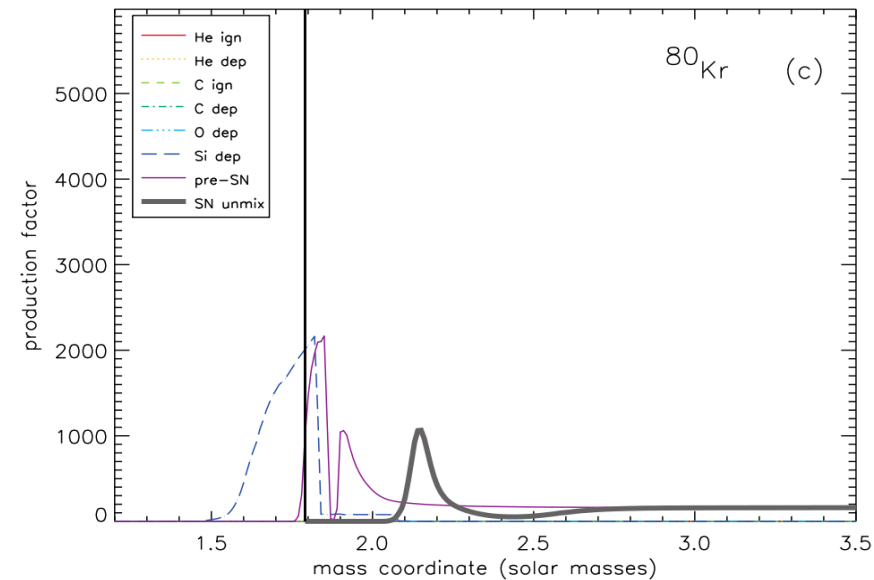
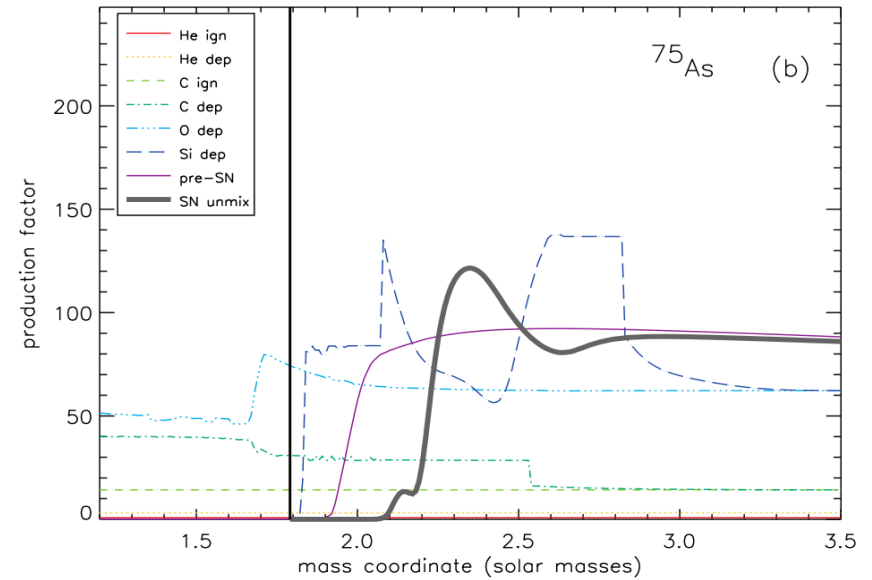
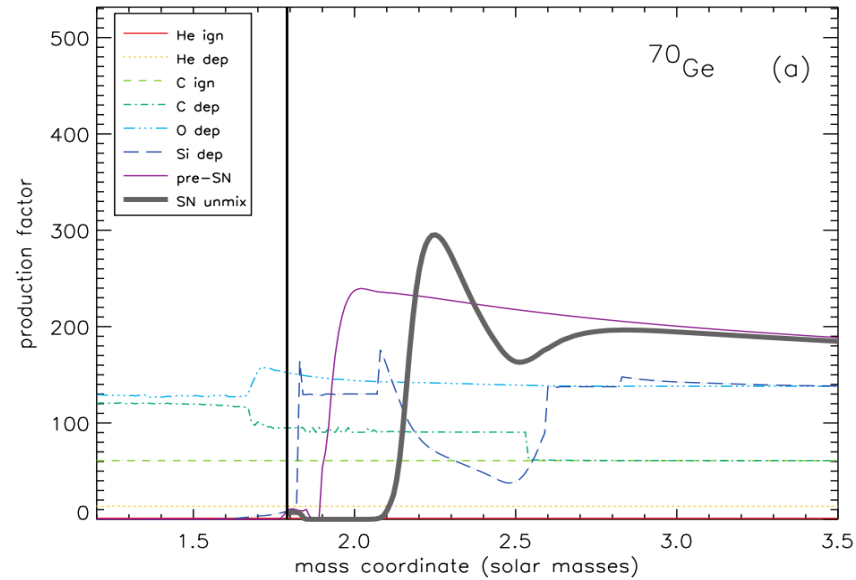
γ -process can be made in implosive O shell burning, but peak abundance is **destroyed by SN** and **recreated further out**



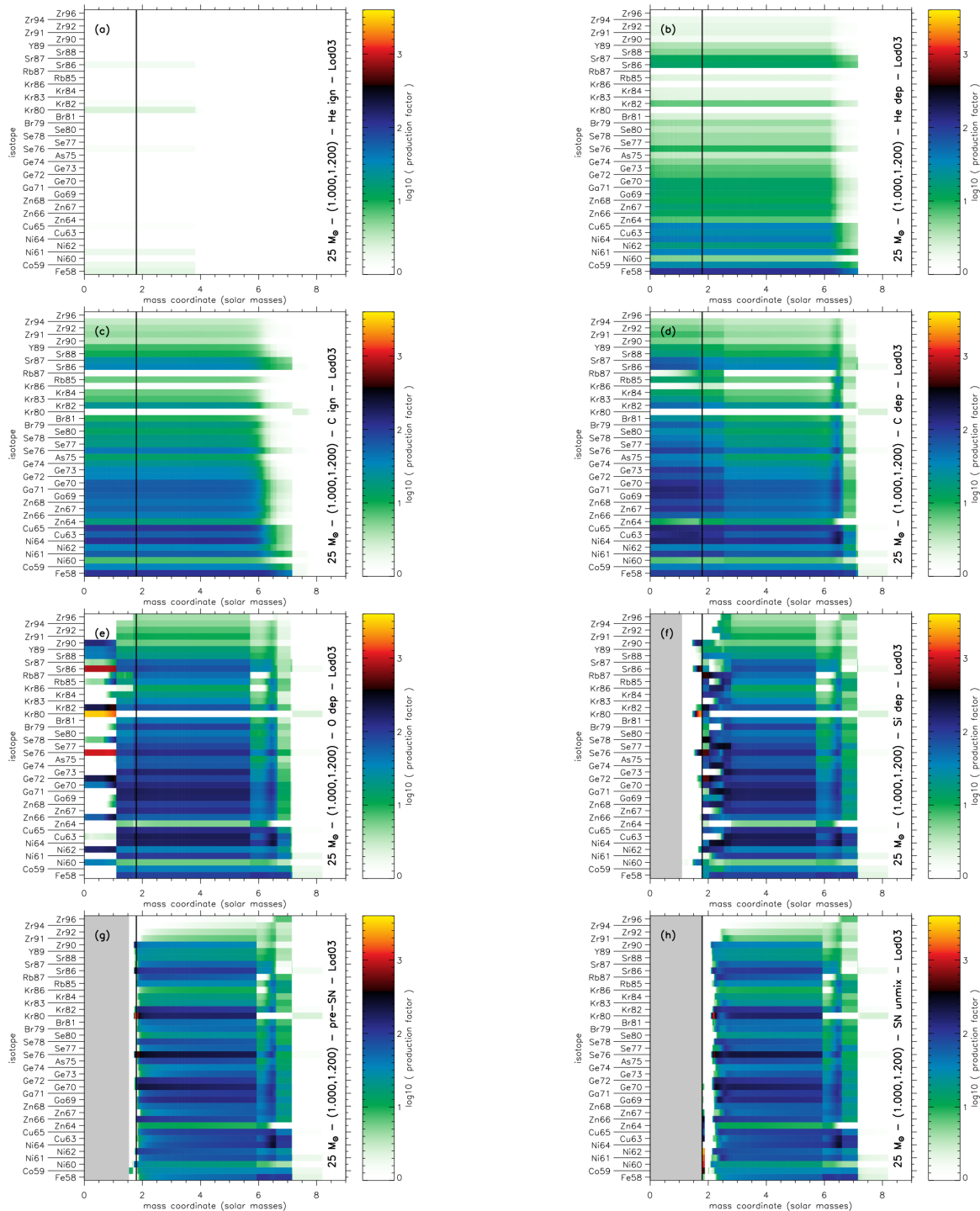
by γ -process and $\bar{\nu}$ -process



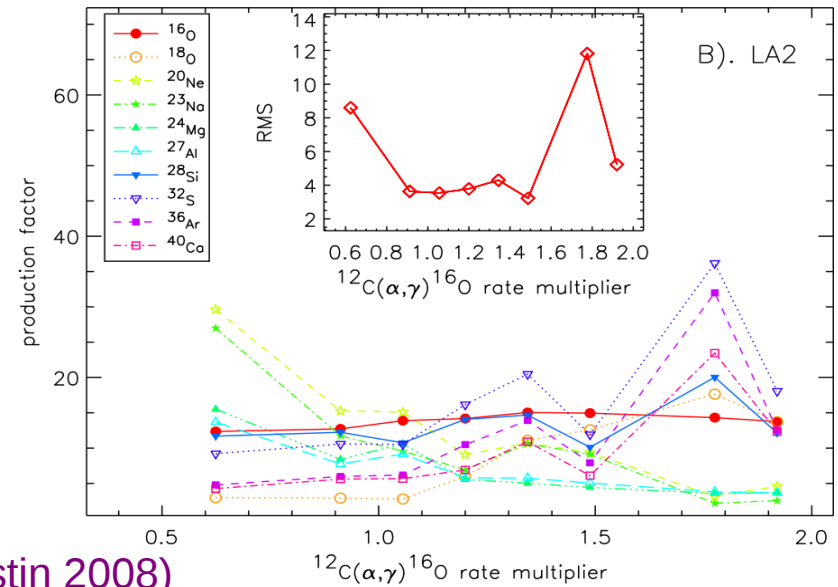
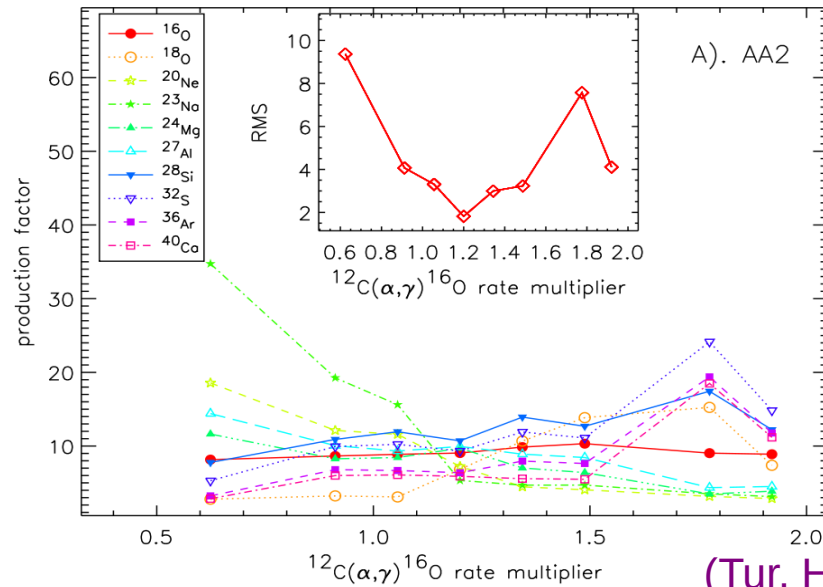
25 Solar Mass Star s-only Yields



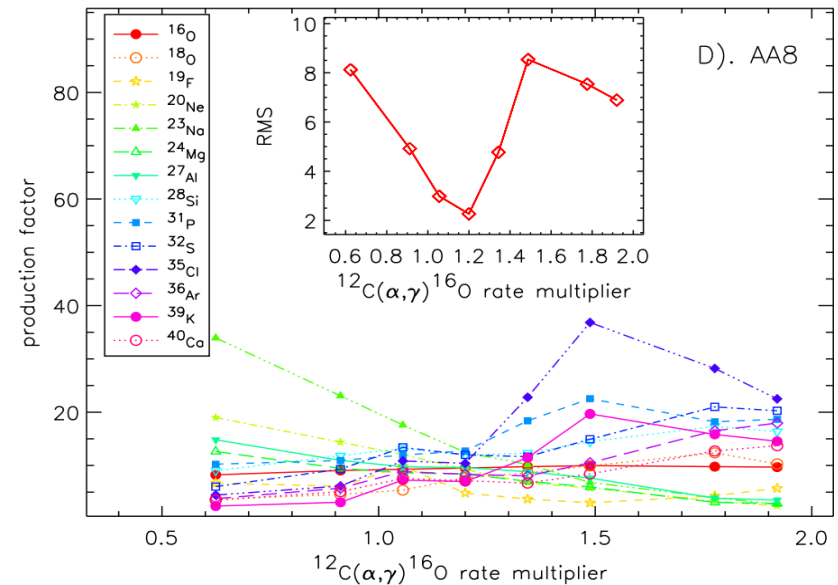
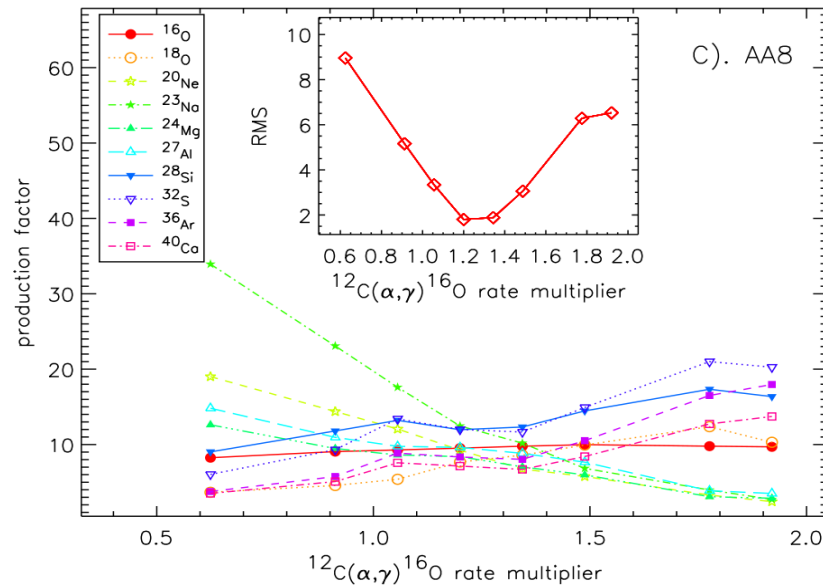
25 solar mass star s-process yields for different evolution stages



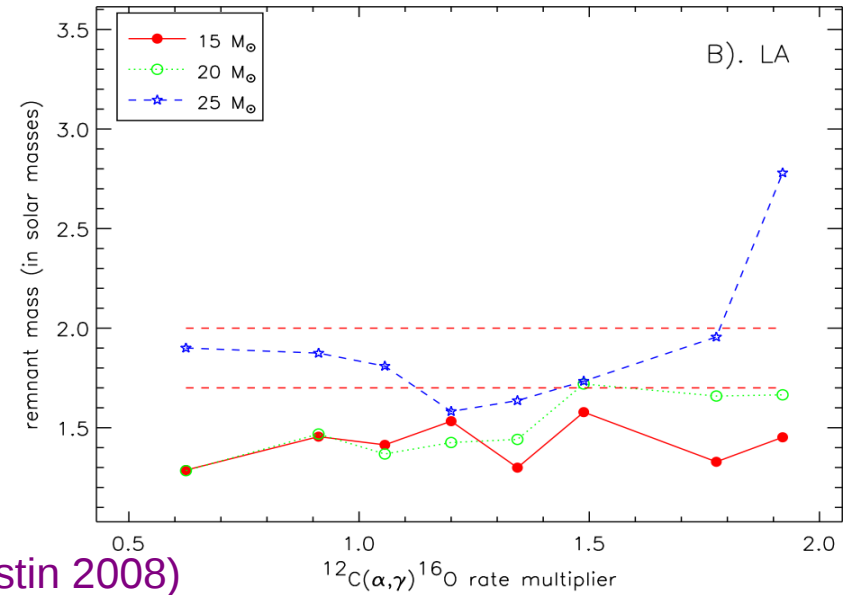
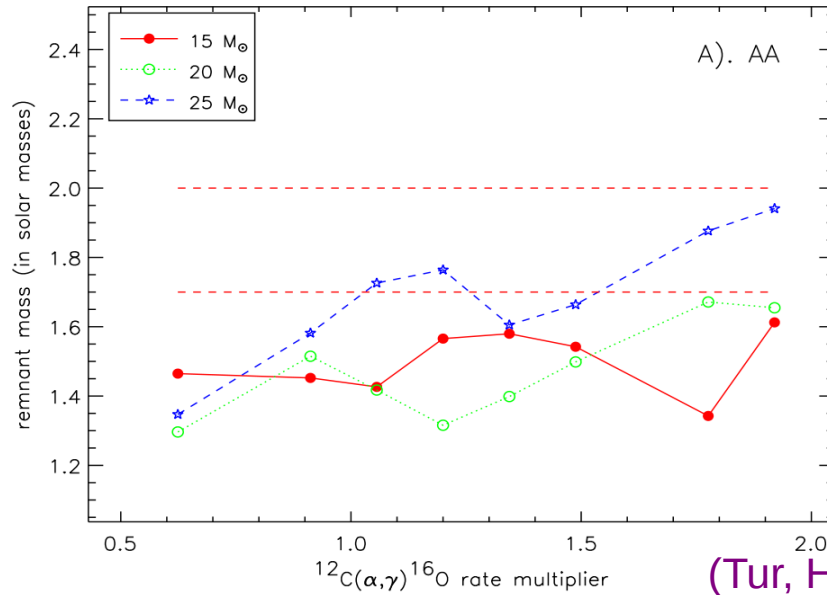
Light Isotope Yields - $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$



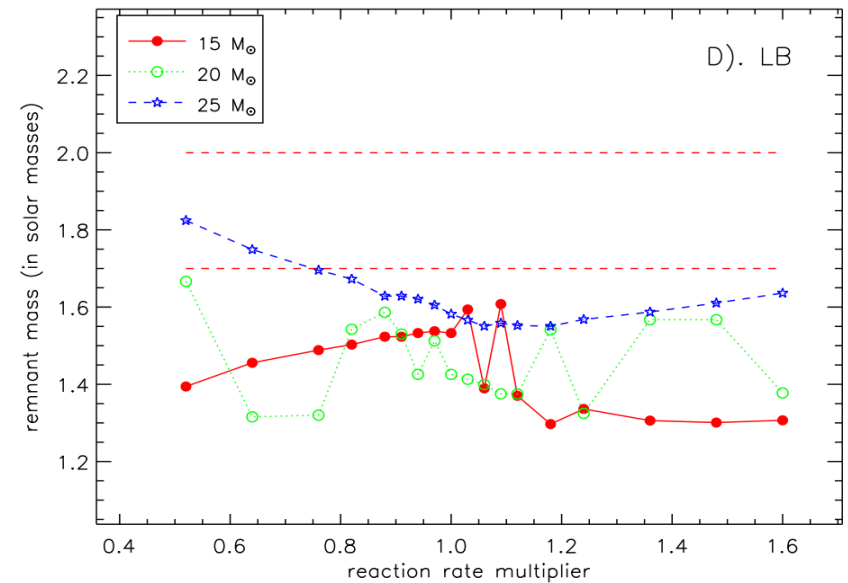
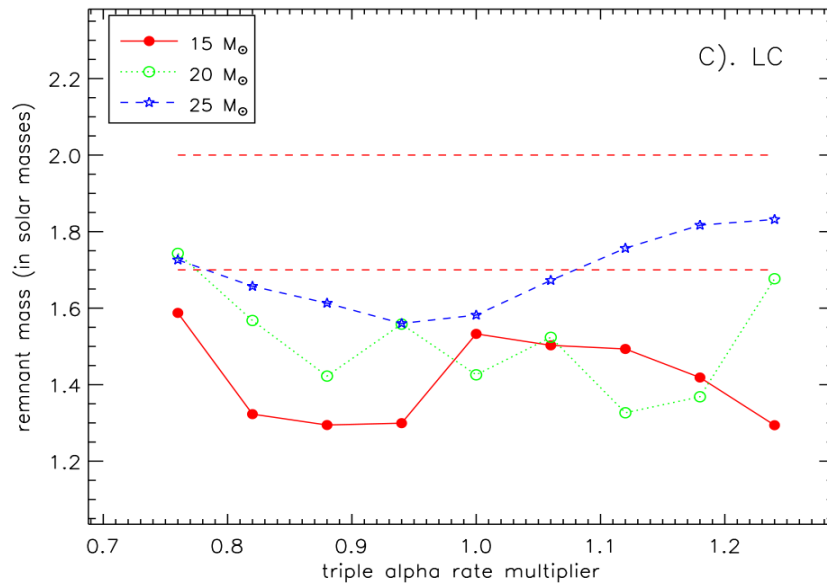
(Tur, Heger, Austin 2008)



Remnant Masses – NS or BH?



(Tur, Heger, Austin 2008)

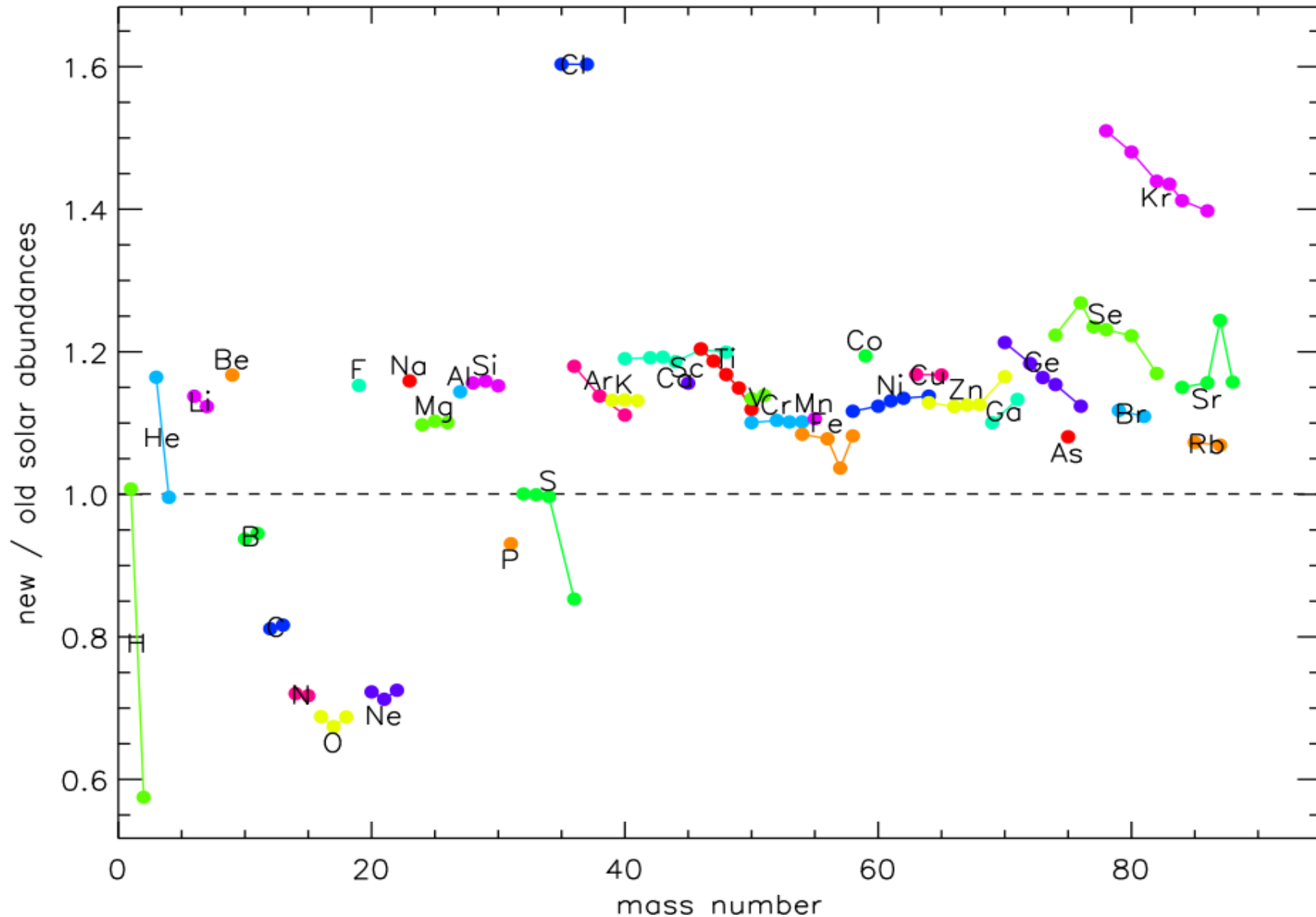


GCE Application

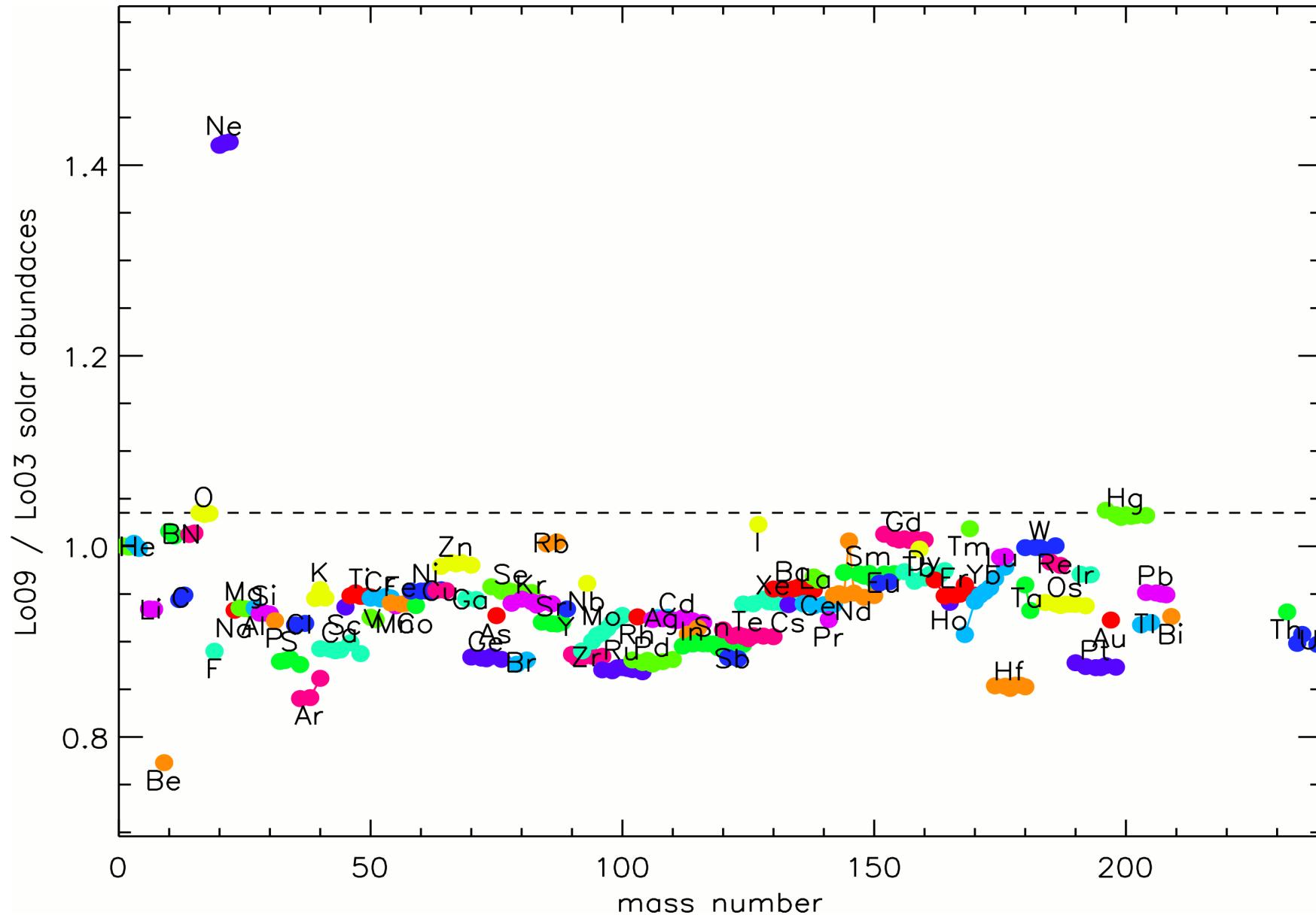
What input do we need for stellar models?

- Initial composition – isotopes(!)
- Initial rotation, binary fraction and parameters
- Nuclear physics – reaction rates, nuclear data
- Stellar physics – “mixing”, winds, binary evolution
- Supernova physics – energies, asymmetries, mechanisms, neutrinos, ...
- Evolution of (isotopic) composition for different environments – star formation histories for dwarf galaxies vs. big ellipticals vs. spiral components, ...

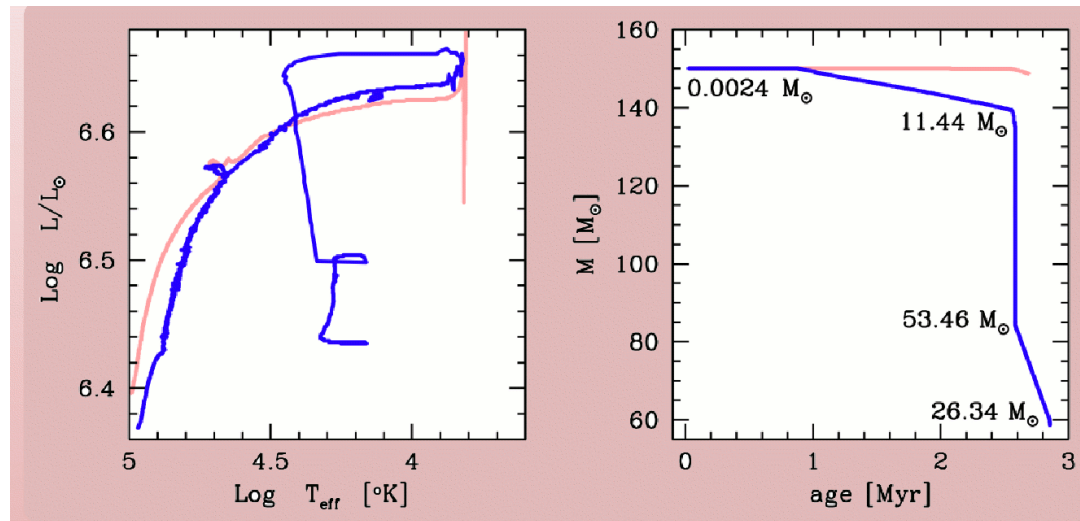
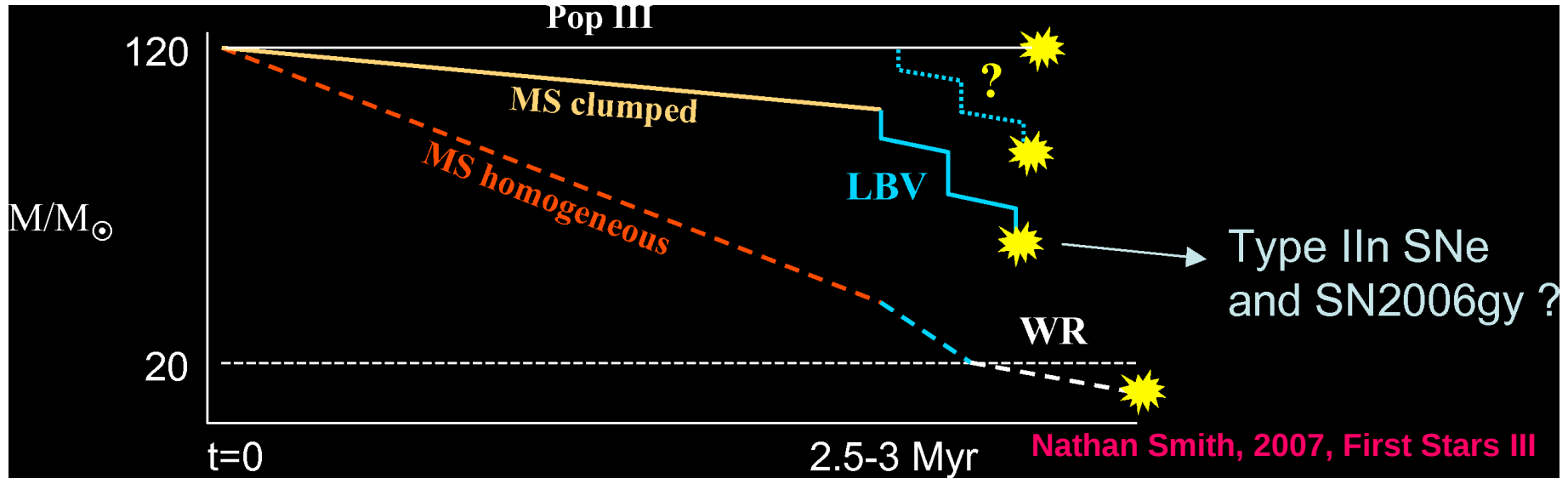
Sun 2.0



Sun 3.0



Mass Loss by Giant eruptions?

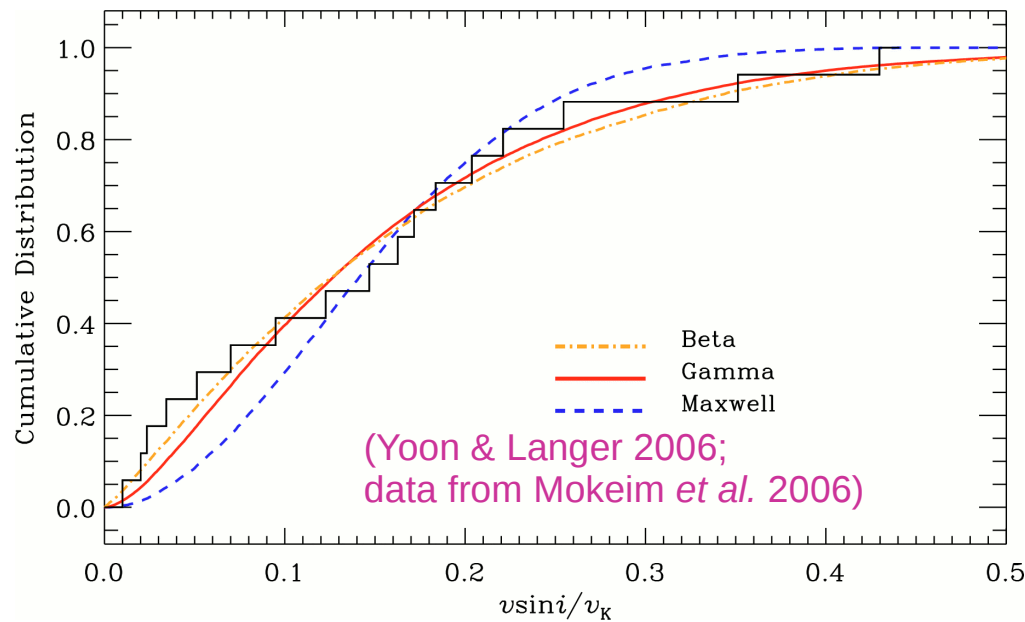


end of central He-burning: $M = 58.05 M_{\odot}$
back at break-up limit

Mass Loss due
to critical
rotation?

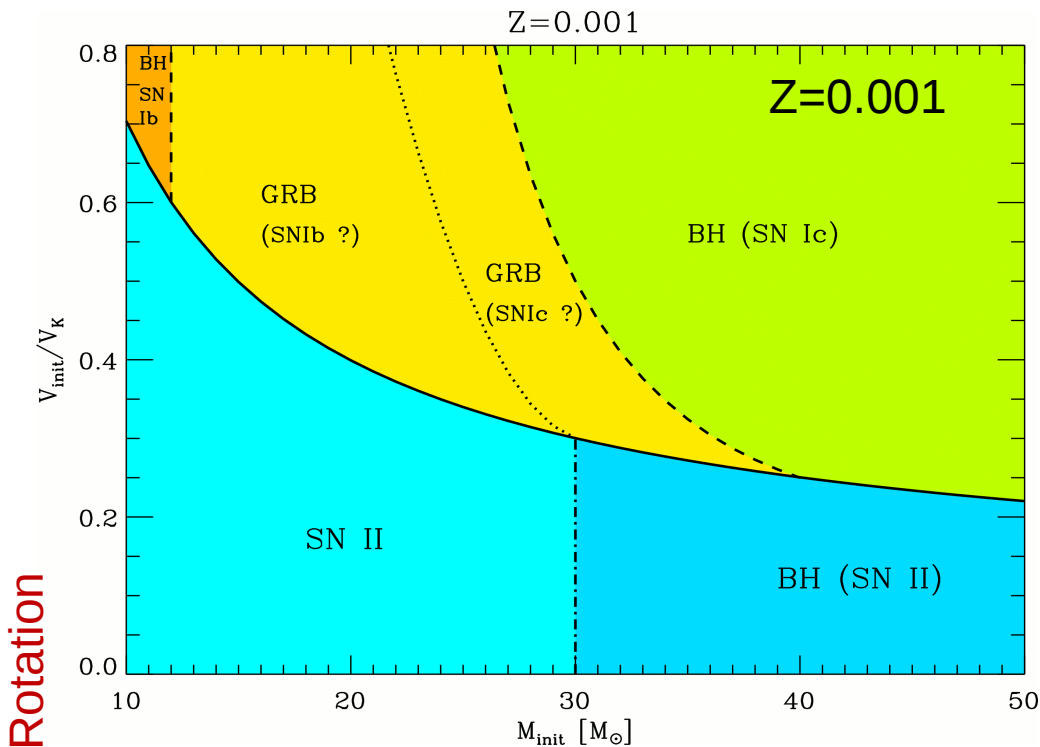
Eikstroem (2007)

Black Holes and GRBs from Rotating Stars



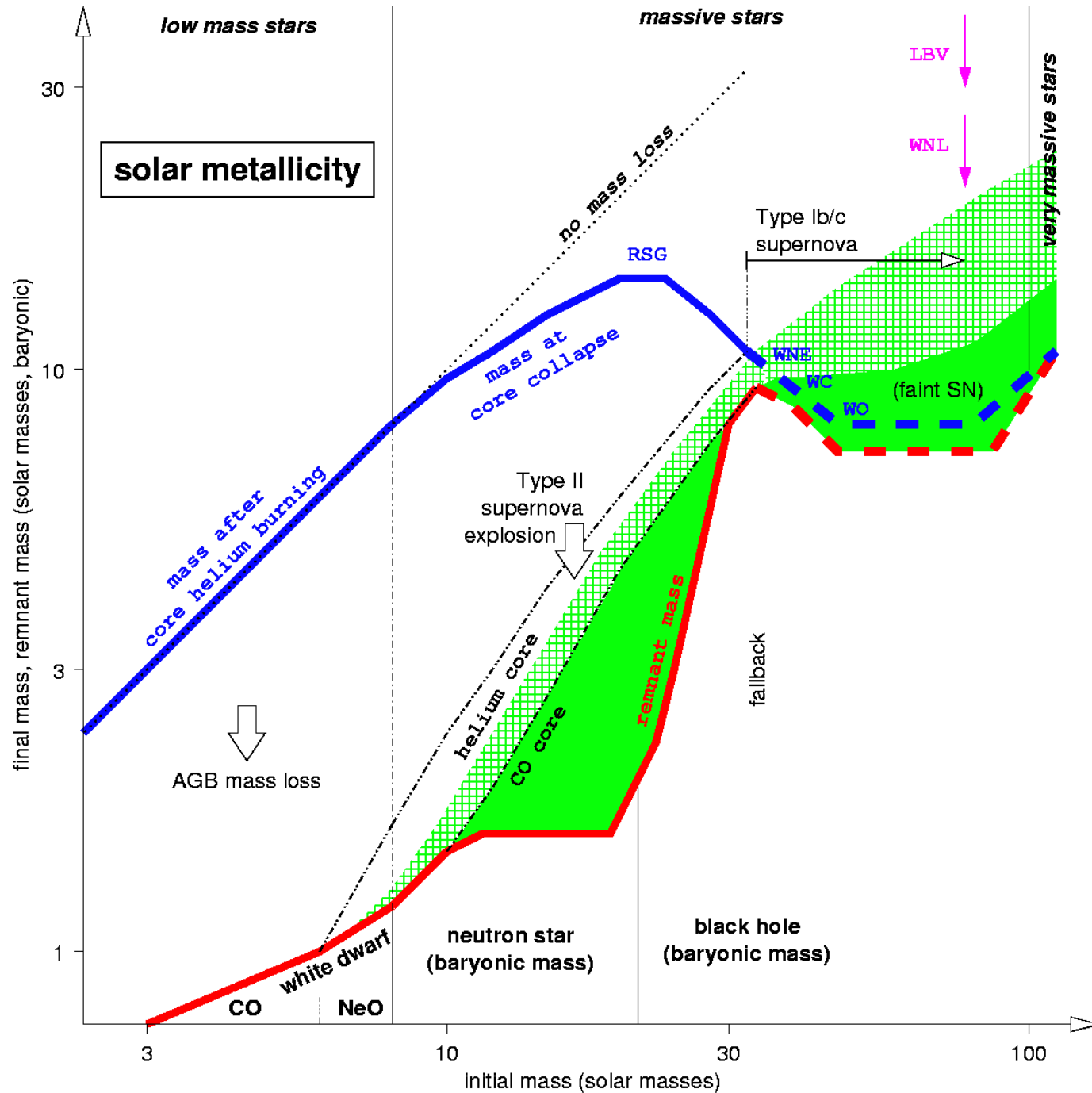
A small fraction of single stars is born rotating rapidly

The fastest rotators evolve chemically homogeneously, become WR stars on the MS, and may lose less angular momentum.

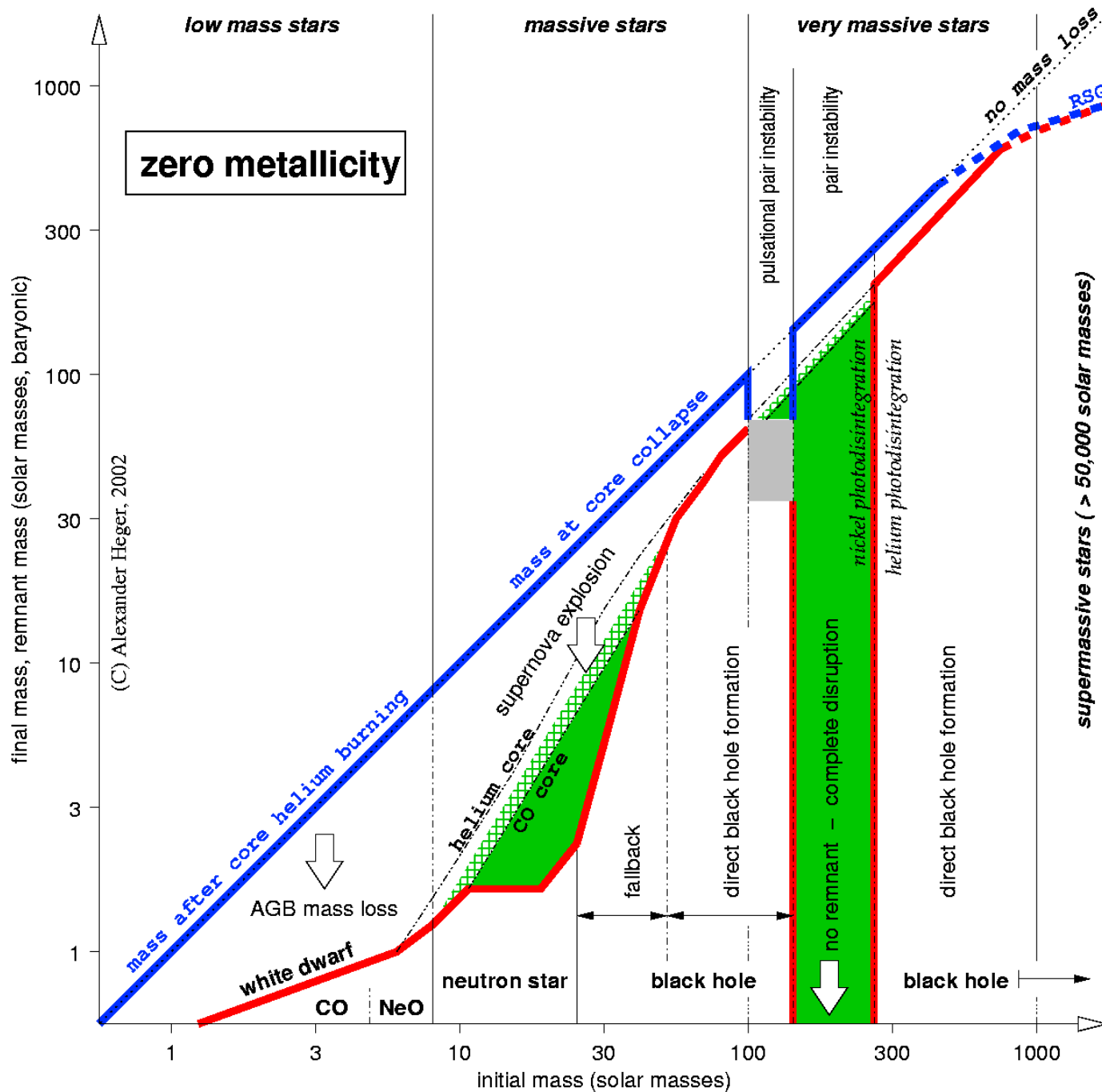


(Yoon & Langer 2006)

Massive Star Fates as Function of Initial Mass (solar metallicity)



Ejected “metals”



Ejected “metals”

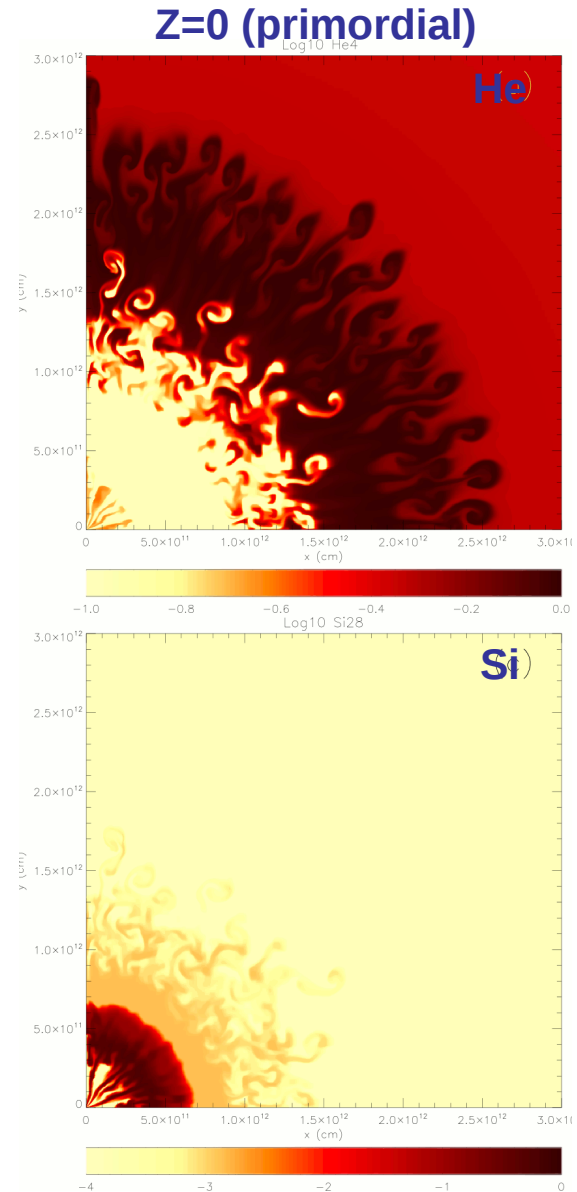
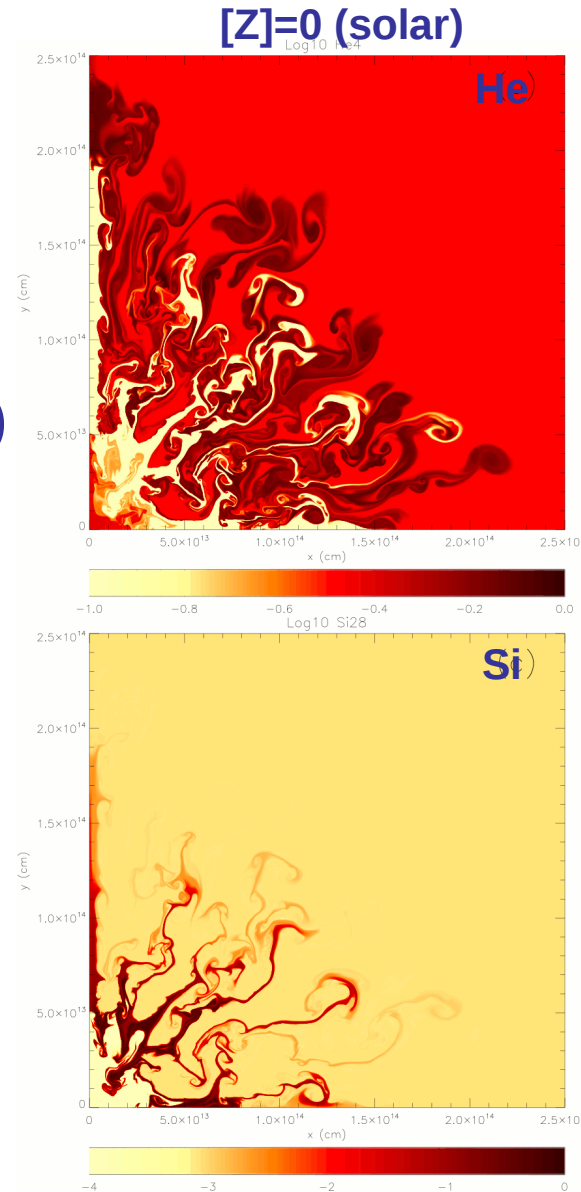
Nucleosynthesis from Stars 10-100 M_{\odot}

Mixing in 25 M_⊙ Stars

Growth of
Rayleigh-Taylor
instabilities

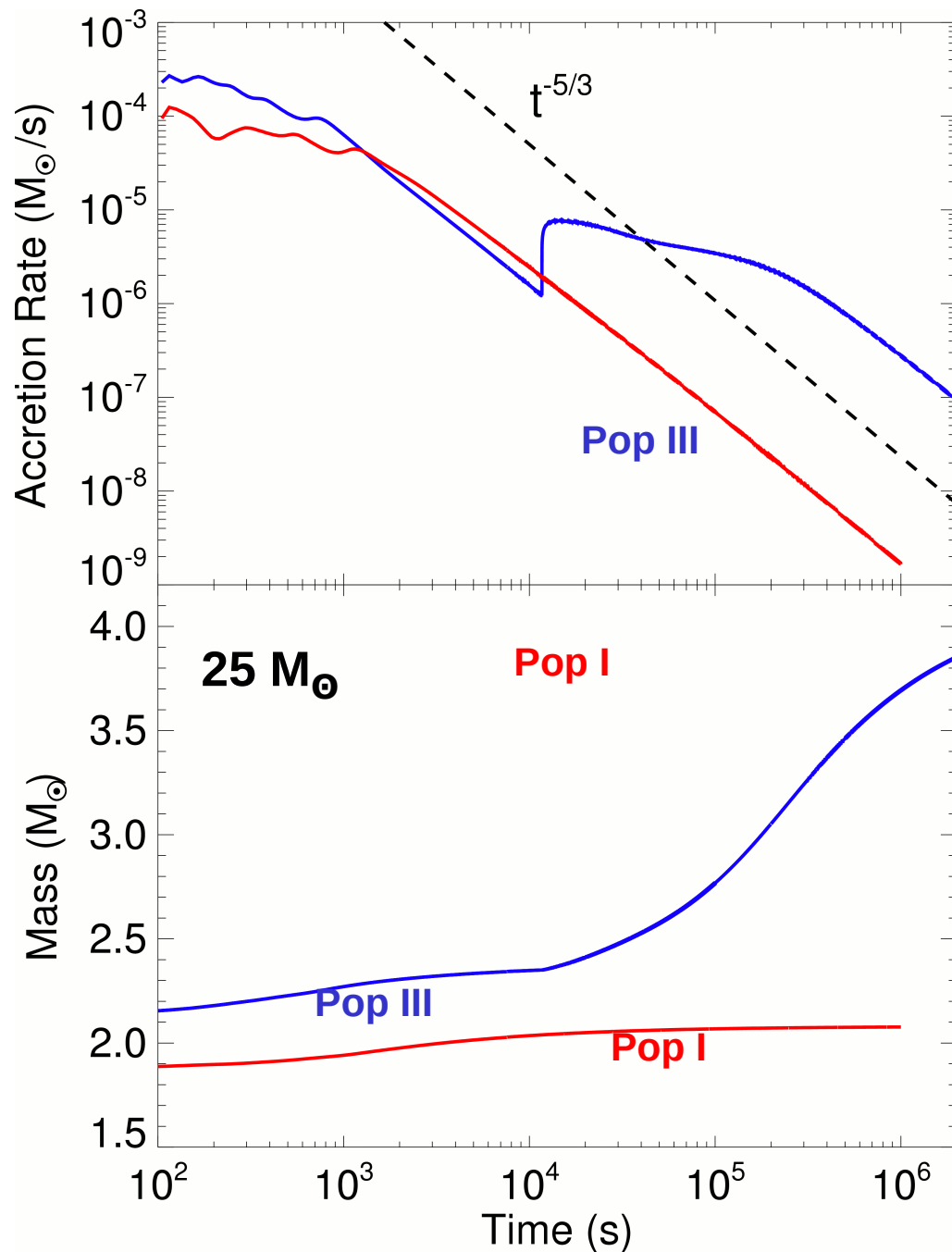
Interaction of
instabilities (mixing)
and fallback
determines
nucleosynthesis
yields

➔ Pop III stars
show much less
mixing than modern
Pop I stars due to
their compact
hydrogen envelope



Simulations: Candace Church (UCSC/LANL T-2)

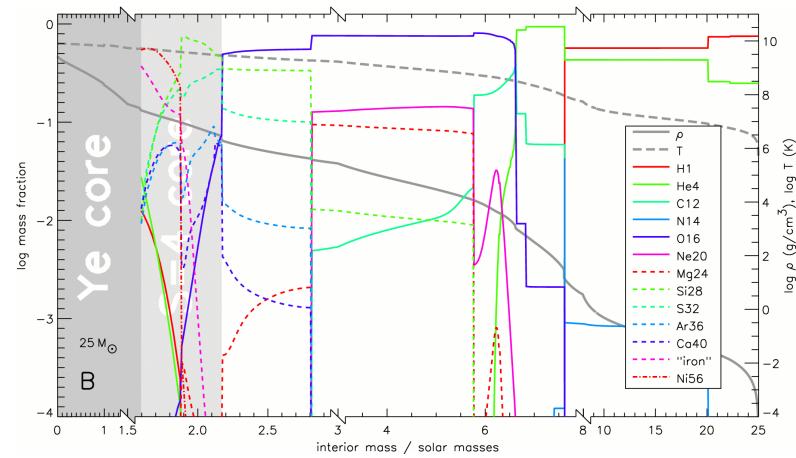
Fallback and Remnants



→ Pop III stars show much more fallback than modern Pop I stars due to their compact hydrogen envelope

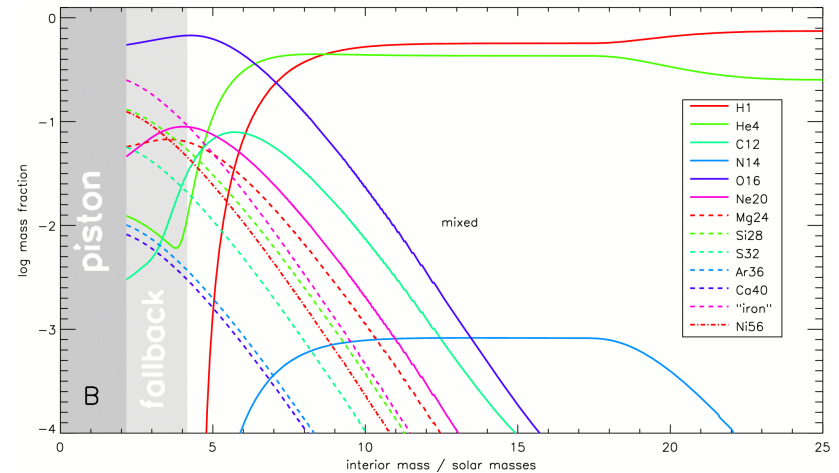
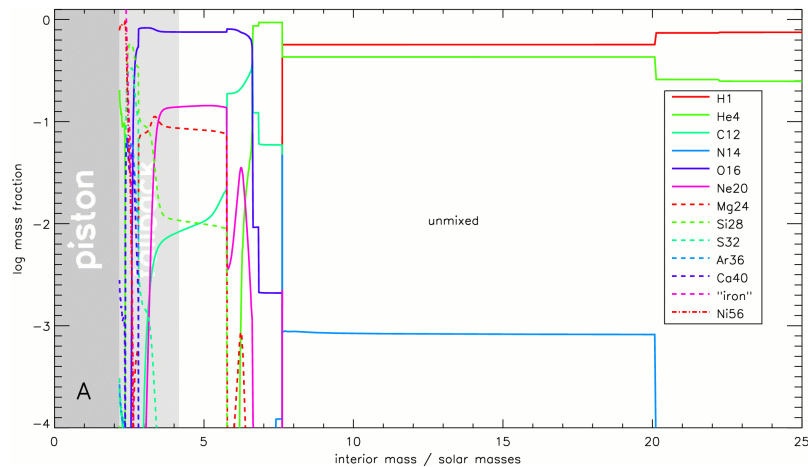
(Zhang, Woosley, Heger 2007)

Supernovae, Nucleosynthesis, & Mixing

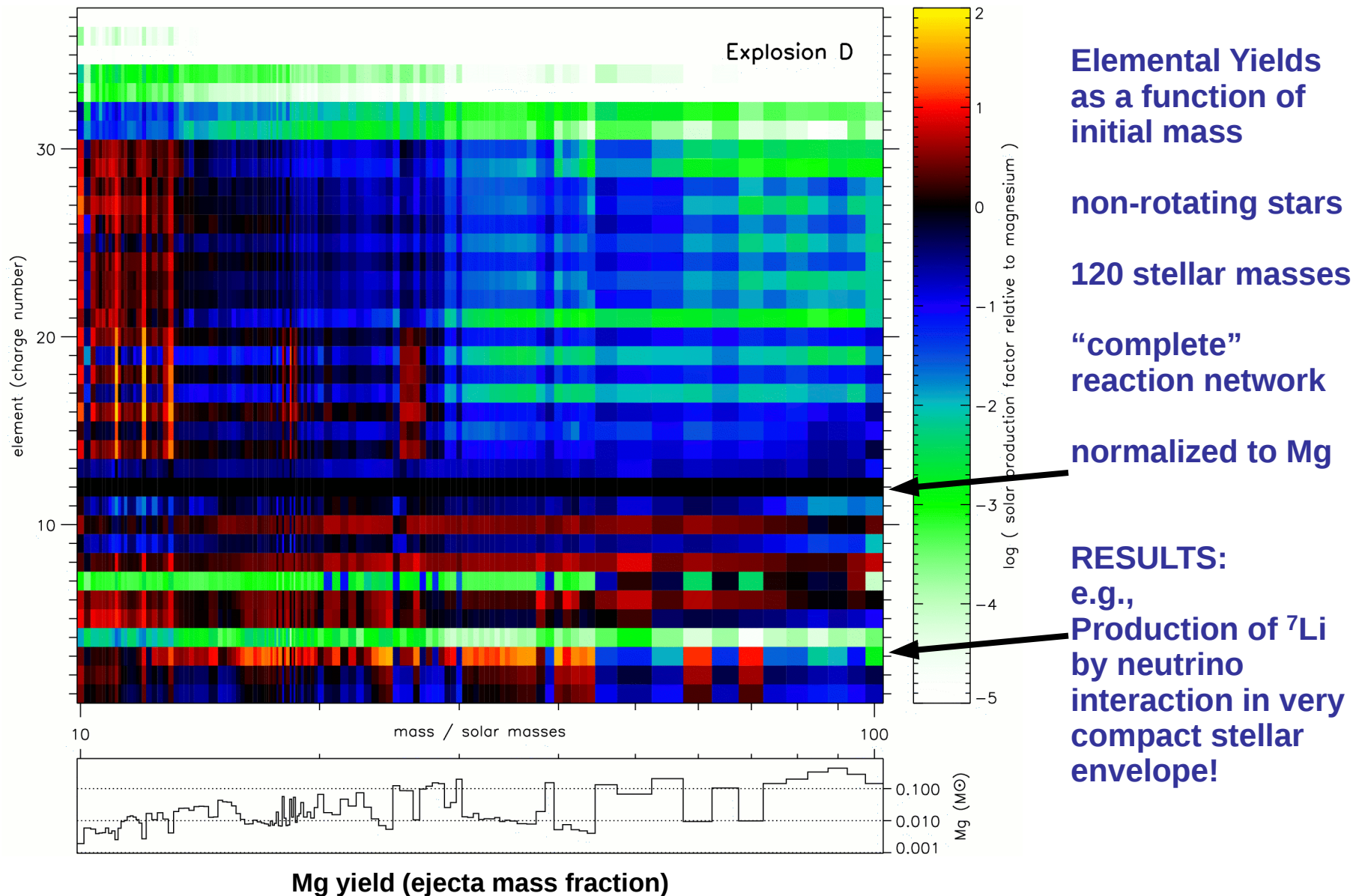


SN, no mixing

SN + mixing

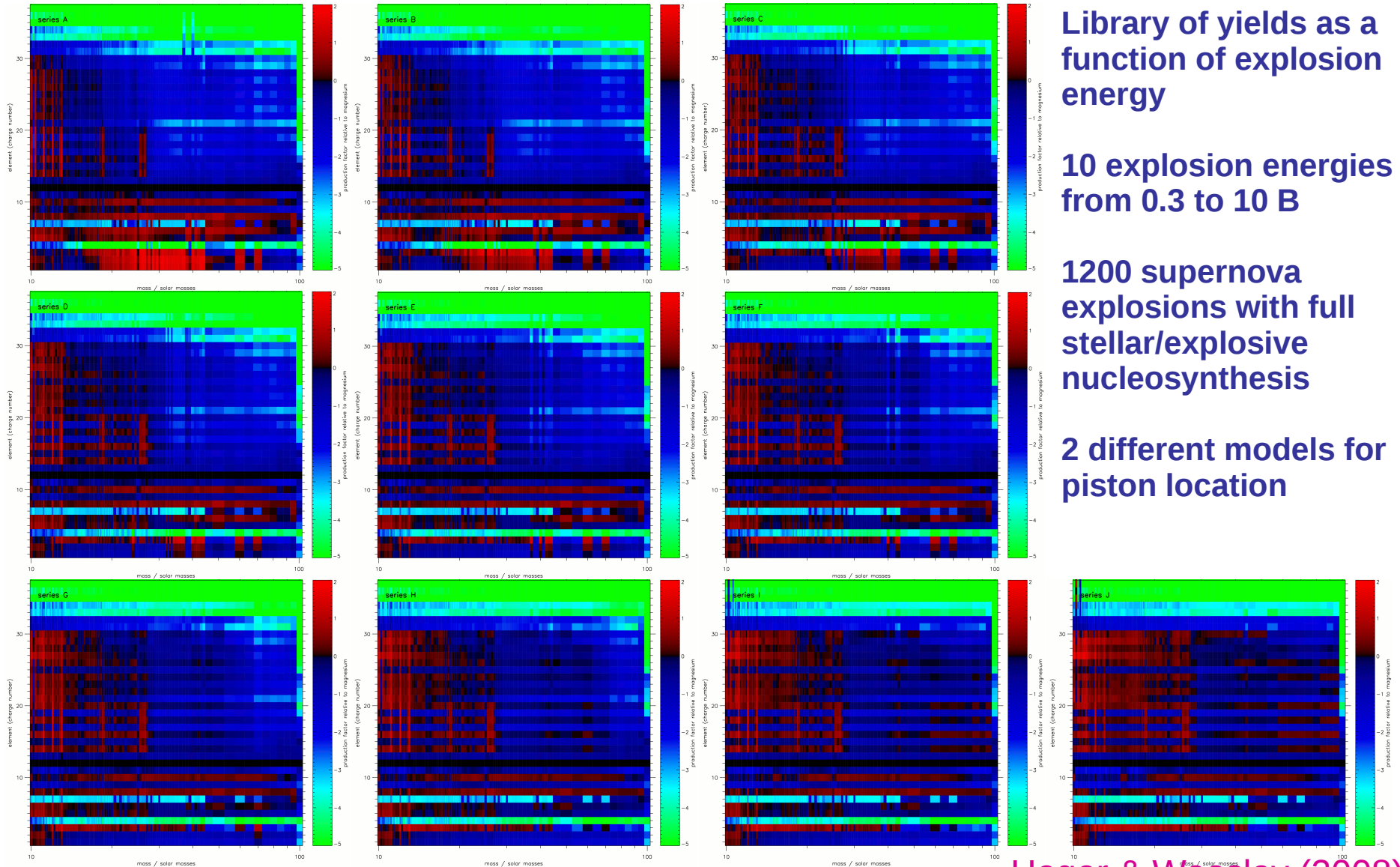


Pop III Nucleosynthesis



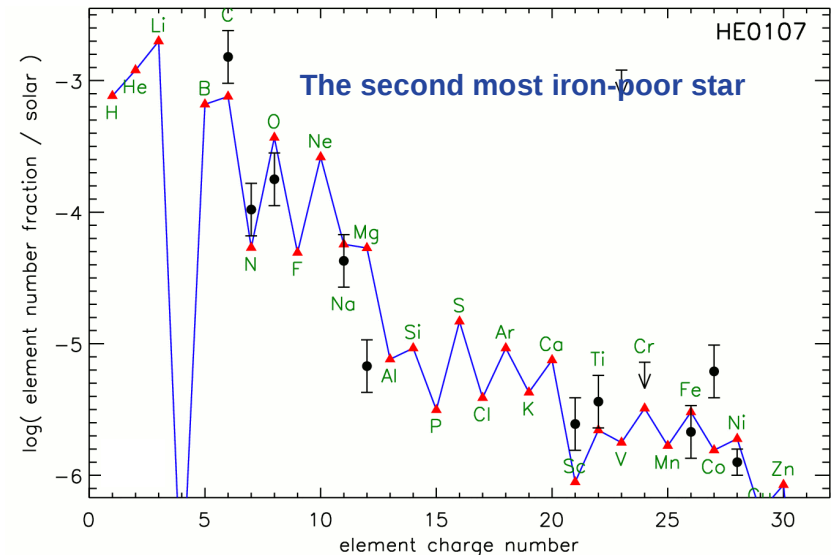
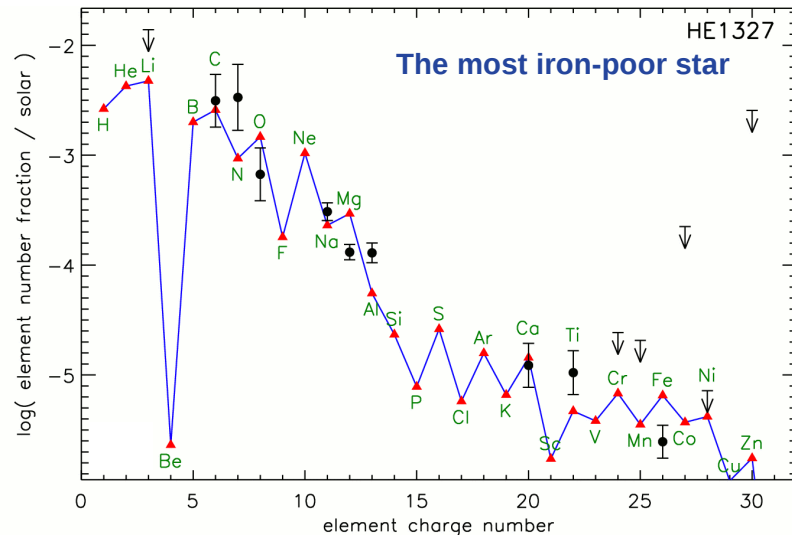
Pop III Nucleosynthesis Grid

data available at <http://starfit.org>

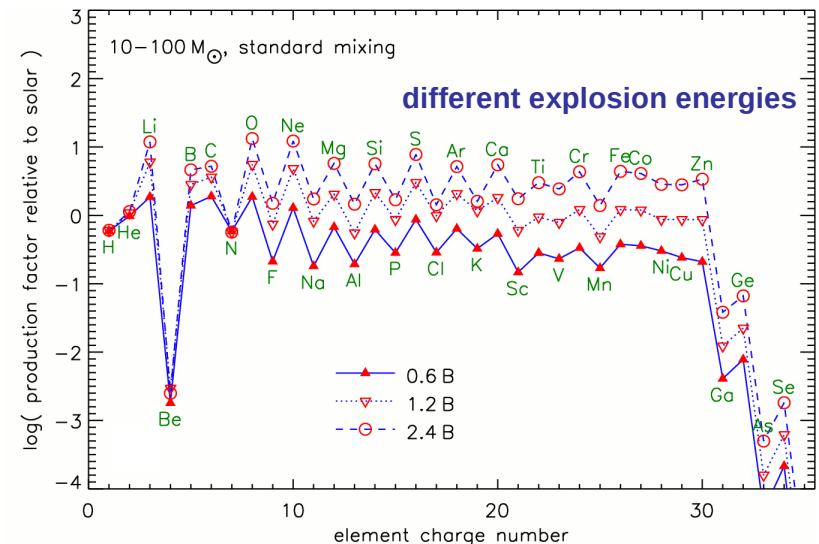
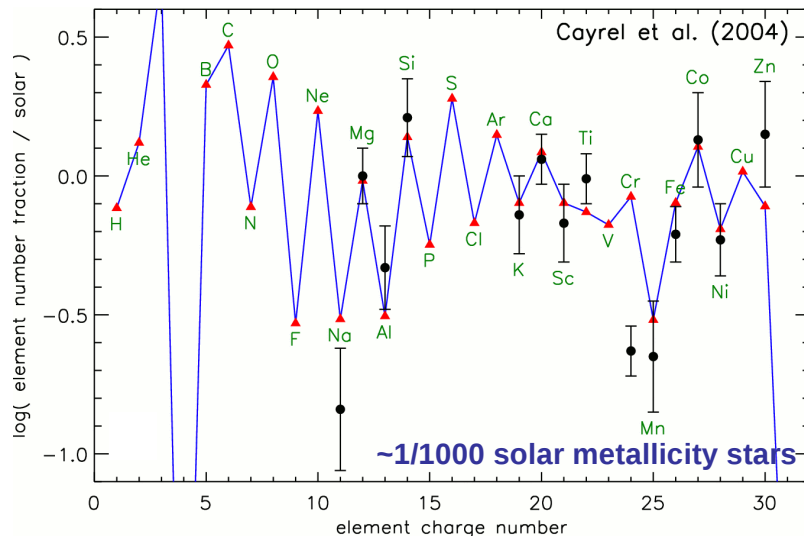


Heger & Woosley (2008)

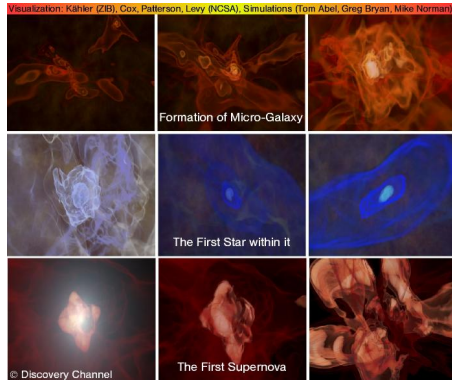
Comparison to Observational Data



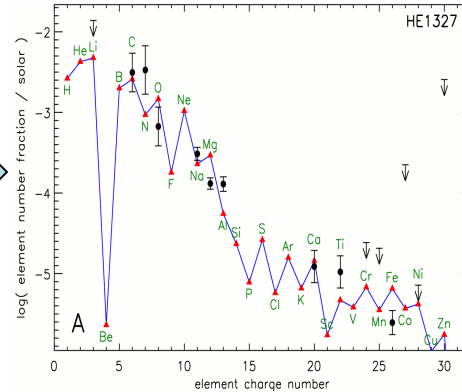
Heger & Woosley (2008)



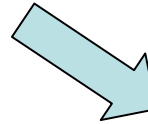
Reconstruction of the IMF



primordial stars form,
nucleosynthesis ejected



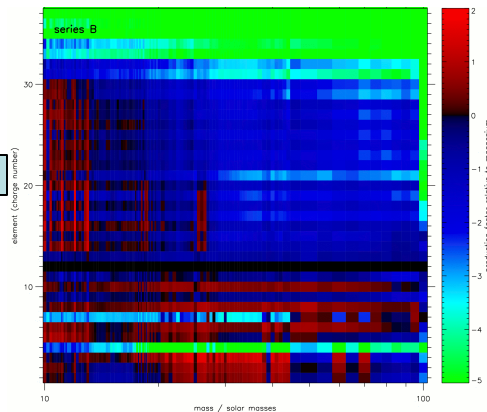
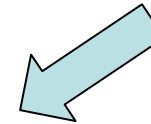
ejecta incorporated
in low-Z halo stars



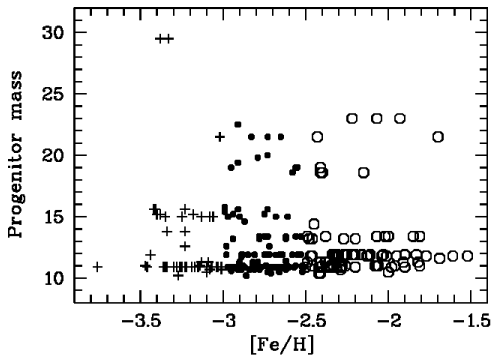
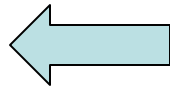
find low-Z halo stars
(HERES, SEGUE, ...)



measure abundances
(VLT, KECK, ...)



compare abundances
to primordial star
nucleosynthesis library

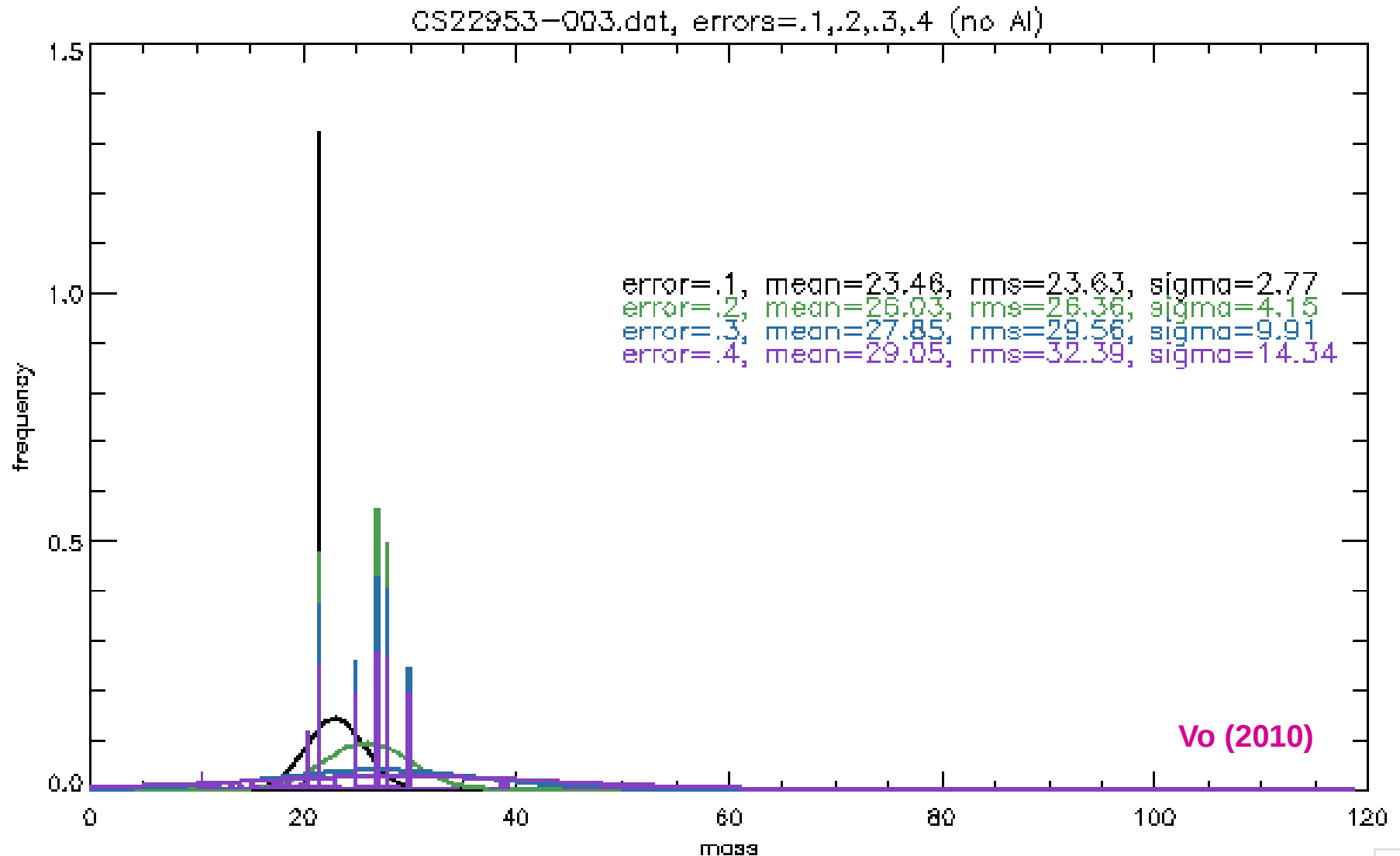


obtain IMF of population
of progenitor stars

Frebel, priv. com. (2007)

Reconstruction of the IMF

Dependence on observational abundance errors



Yield Data

- Data base format for yield data (**stardb**)
isotopes, radioactivities, elemental molar, ...
as function on input parameters
- Single star zonal outputs
“user” can combine as needed (e.g., pre-solar grains)
- Fit (and plot) tools **starfit** (starfit.org)
- Observers: please provide data in **log ϵ** ,
better: mol fractions (mol/g)

Summary

- **Understanding stars and the origin of the elements requires input from many fields of physics**
- **Stellar nucleosynthesis requires detailed and complete stellar models from formation through death and explosion**
- **CCE models require integration of environment and stellar models**
- **Useful constraints require on CCE detailed and accurate abundance measurements**